REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
07/21/2011

2. REPORT TYPE

3. DATES COVERED *(From - To)*
01/03/2010-28/02/2011

4. TITLE AND SUBTITLE
Observations and Predictions of Bedforms in Tidal Inlets and River Mouths

5a. CONTRACT NUMBER
ONR-N00014-10-1-0643

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Gallagher, Edith L.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Franklin and Marshall College

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Franklin and Marshall College

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long term objective of the proposed study is to model and measure bedforms in tidal inlets and river mouths. We use an existing self-organization model to predict multiple scales of bedforms and we will make measurements of bedforms within combined flow environments (May 2012). The model's predictive skill will then be evaluated. This grant was for 1 year only and included funds to begin model development, to interact with the CSDMS group, and to participate in an ONR program review (June 2010). These activities have all been completed and a follow-on ONR grant has been awarded.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
u	u	u	uu		Edith Gallagher / 717-291-4055

PREDICTIONS OF BEDFORMS IN TIDAL INLETS AND RIVER MOUTHS

Edith L. Gallagher
Biology Department
Franklin and Marshall College
PO Box 3003
Lancaster, PA 17604-3003
phone: (717) 291-4055 fax: (717) 358-4548 email: edith.gallagher@fandm.edu

Award Number: N00014-11-1-0155

LONG-TERM GOALS

The long-term goals of the study are to model and measure bedforms in tidal inlets and river mouths. Specifically, the goals are: 1) to use an existing self-organization model to predict multiple scales of bedform formation, growth and migration in combined steady, tidal and wave-driven flows, 2) to compare model predictions with measurements (from both the literature and from a tidal inlet/river mouth experiment), 3) to test the hypothesis that subaqueous bedforms will grow indefinitely for a given set of conditions and that different scales of bedforms will occur simultaneously because of this continuous growth, and 4) to incorporate this bedform model into community modeling systems (eg CSDMS) to improve modeling of flow, sediment transport and morphology change in river mouths and tidal inlets.

OBJECTIVES

The specific objectives of this study have been to

- develop and adapt the present model for flows in river mouths and tidal inlets (expand the model to 2-D flows, improve flow drivers, scale the model up for larger spatial domains and begin to examine multiple bedform scales).
- continue working with the CSDMS so that the present model can be utilized by that community modeling environment.
- participate in the ONR-supported tidal inlet and river mouth experiment with Tom Lippmann at CCOM/UNH to generate a data set on bedforms in a tidal inlet.

APPROACH

Bedforms in sandy environments are ubiquitous, occurring in rivers, river mouths, estuaries, tidal inlets and on open-coast beaches. Bedforms act as roughness elements, altering the flow and creating feedback between the bed and the flow. In doing so, they are intimately tied to erosion, transport and deposition of sediments (eg Parsons et al. 2005, Ernstsen et al. 2005). It has been suggested that bedforms in rivers and tidal inlets are dynamically similar to Aeolian dunes and bedforms on the continental shelf and in the surf zone (Best 2005, Frank and Kocurek 1996, Nemeth et al. 2007, Gallagher 2003). Because of this similarity, Gallagher (2011) developed a model for bedforms in the nearshore, based on the principles of work by Werner (1995), who hypothesized that Aeolian dunes were self-organized features and as such could be modeled with a relatively simple model.

It has been suggested that self-organization is responsible for the formation of many different types of morphological patterns, including river meanders (Stolum 1996), sorted-patterned ground (Kessler & Werner 2003), beach cusps (Coco et al. 2000), wind ripples (Nishimori & Ouchi 1993) and Aeolian dunes (Werner 1995, Reffet et al. 2010). In each of these pattern-forming systems, complexity arises from nonlinear interactions between the system and the environment, from dissipative processes such as friction, turbulence and sediment transport, and from being open (both material and energy are exchanged across system boundaries) and therefore never in equilibrium (Werner 1999).

Werner (1995) used a 'hierarchical' approach (Ahl & Allen 1996) to modeling self-organized systems, wherein processes at different temporal and spatial scales are distinct from each other and can be separated. With this approach, grain-scale sediment transport is parameterized with simple rules to drive bedform-scale dynamics. Gallagher (2011) developed a hierarchical model to predict nearshore, combined flow megaripples. The model consists of a matrix of sediment slabs that represent a spatial domain or a region of a bed across which sediment is moving. The sand slabs are picked up and moved according to a transport model (either simple rules similar to Werner (1995) or a physics-based formulation, e.g. Bailard 1981, Ribberink 1998). Sediment transport is driven by the free stream velocity, u, which is modeled with a sinusoidal velocity, a measured velocity signal from the natural surf zone or with a Rayleigh distributed wave velocity signal. At each time step, the flow is the same at all locations in the domain except for an imposed random spatial fluctuation representing local turbulence. However, once bedforms are created, the flow around the bedforms is altered via feedback: flow is reduced in the lee of a bedform to simulate a velocity shadow zone and flow is accelerated over the crest of a large bedform. These spatial alterations to the flow generate gradients in transport, which alter the bed. Feedback is required for bedform growth and development (Gallagher 2011). In addition, the slope of the bed is not allowed to exceed 17^{o}.

The long-term plan for this research is to work with and adapt the self-organization model, developed for nearshore bedforms. This model is being adapted for predicting bedforms in the combined flows of tidal inlets and river mouths. In these environments, oscillatory flows with wave frequencies are superimposed on the quasi-steady flows associated with tides (oscillatory but with a much longer period than the surf waves) as well as steady flows (possibly with seasonal variations) exiting river mouths. These complex, but naturally realistic, flows are being incorporated to predict the growth and migration of dunes and the evolution of multiple scales of bedforms. In addition to combined flows and multiple scales, variations owing to spatially varying grain size will also be examined. This model lends itself to tackling these dynamically complex issues, because relatively simple changes can be implemented to test the importance of factors such as lateral flows, feedback changes, grain size and subtle 3-D morphology changes. Model results will be compared with data from the literature (eg, Hanes 2012 , Jerolmack and Mohrig 2005, Ernstsen et al. 2005) and with data collected as part of the River Mouths and Tidal Inlets DRI experiments in collaboration with Tom Lippmann (UNH), Steve Elgar (WHOI) and Peter Traykovski (WHOI).

Lastly, the model has been submitted to the Community Surface Dynamics Modeling System. CSDMS is a community of experts promoting open-source modeling of earth surface processes. They develop, support, and disseminate integrated software modules that predict the movement of fluids and the flux of sediments and solutes in landscapes and sedimentary basins (for more information see their website at http://csdms.colorado.edu/wiki/Introduction). Here, the bedform model can be used and improved by others and integrated into larger-scale fluid and morphodynamic models with the intention of improving predictions of, bed roughness, wave and flow dissipation, and sediment transport.

WORK COMPLETED

Significant progress has been made in adapting the bedform model for river mouths and inlets (see Fig 1 for a schematic). The flow model, which drives sediment transport and bedform dynamics, has been extended from 1-D to 2-D. Preliminary results suggest that this advance has improved model predictions significantly by adding complexity and slowing the bedform formation process (Fig 4). Other improvements to the model flow field that have also improved predictions are the addition of a Rayleigh distributed wave field and the addition of flow-dependent turbulence.

The original MATLAB version of the model is available on the CSDMS website. The model has been translated from MATLAB to Fortran to fascilitate increasing the domain size and running on the CSDMS High Performance Computing Cluster. The model is now being run successfully (and speedily) for larger domains. In addition, with a Fortran version, the model can be included as a 'component' in CSDMS making it easily integratable with other models. Currently, I am sitting in on a computer science course to learn the Python programming language. The CSDMS staff scientists have recommended Python as a more modern and flexible language for modeling. Thus I am moving in the direction of translating the model into Python as well. (I am learning a lot!) These steps are considered neccesary in the model development, although in themselves they do not produce interesting or measureable results.

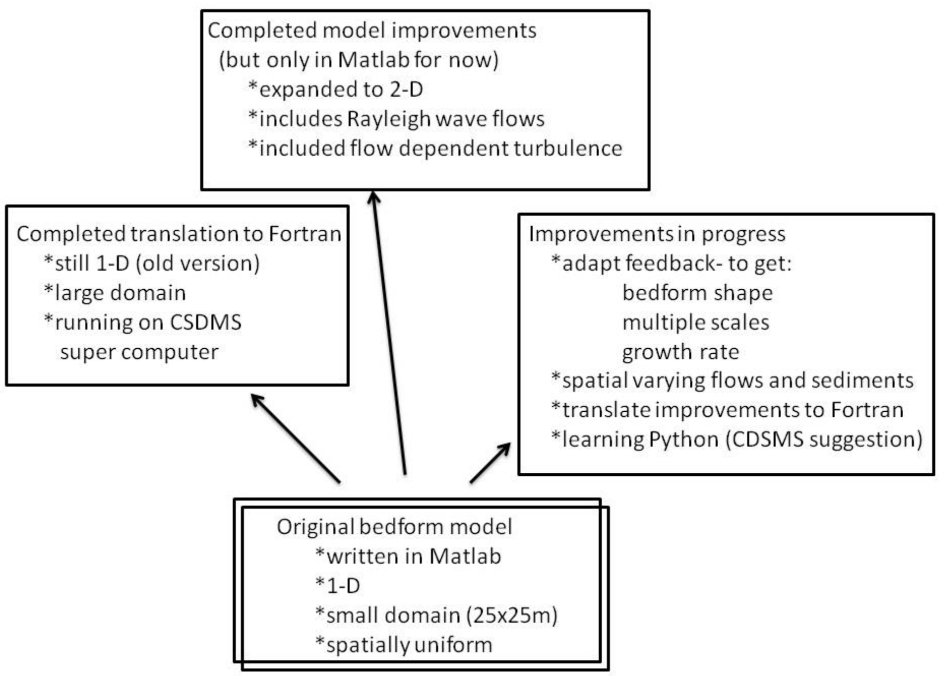

Figure 1. Flowchart of model improvement completed and underway.

In addition to these coding/computer science aspects of the model improvement a number of model adaptations are being considered to improve the model's accuracy. With the increased domain size now possible, the model needs to have spatially varying flow and bed domains to realistically reproduce the larger scale tidal inlet regions to be modeled. (In contrast to the smaller nearshore megaripple domain, where the flow was spatially uniform.) In addition, the model feedback is being adapted to create more realistically shaped bedforms and to (hopefully) improve the predicted growth dynamics (Fig 4). In this case, a crude mechanism for suspended load bypassing will be included in the feedback/transport routines (this is in its infancy).

I presented the model at the ICCE 2012, AGU Fall Meeting 2012 and received lots of excellent feedback. I hope to establish a collaboration with modelers at UPC (Universitat Politecnica de Catalunya. We have discussed a meeting next summer during the RCEM conference). The model was also presented at the ONR program review in September 2012 in Denver and at the New River Inlet Experiment (see below) Review in April 2013 (despite no funding).

I participated in the tidal inlet experiment at New River Inlet with Tom Lippmann in May 2012. Preliminary bedform data from that experiment (collected using a multibeam sonar to make detailed bed measurements and using rotary side scan (Traykovski)) are exciting and suggest multiple scales of bedforms exist, that bedforms vary significantly depending on depth, sediment availability and that these bedforms are changing constantly as the waves and tides change. Some examples of Traykovski's preliminary data can be seen at http://vimeo.com/44806773. In these movies, multiple scales of bedforms are observed to form, change directions, be destroyed and reform over the course of a tidal cycle. Through collaboration, these data sets will be used to test the model.

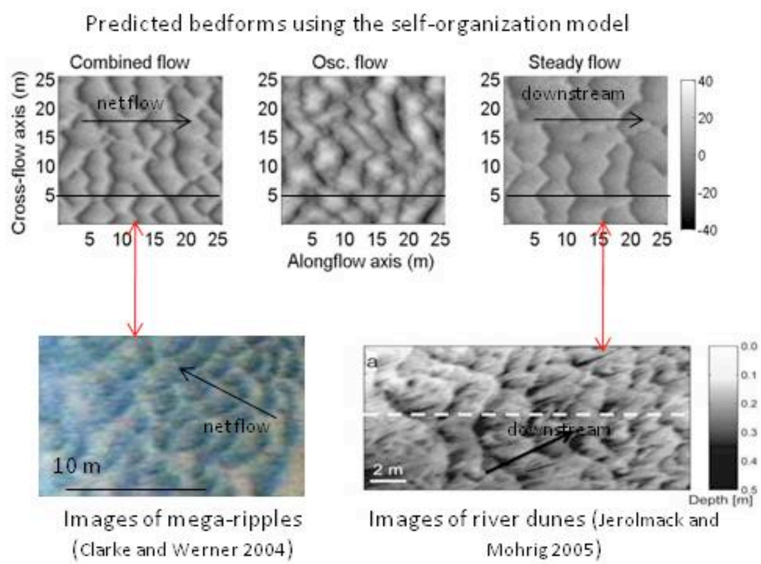

Figure 2. Top row: modeled bedforms for combined (oscillatory and steady) flows (left), oscillatory flow only (middle) and steady flow only (right). Oscillatory flows have a period of 10 secs and an amplitude of 75 cm/s (left) and 95 cm/s (middle). The steady flows were 20 cm/s (left) and 50 cm/s (right). Bottom row: observed bedforms. Red arrows show the correspondence between similar modeled and observed features.

RESULTS

This model was developed for nearshore flows (combined waves and currents) and sediment transport. Predicted nearshore bedforms are shown in Fig 2 (top left) and are similar to observed features in the surf zone (Fig 2, bottom left, from Clarke and Werner 2004. See also Gallagher 2003). Altering the forcing flow field in a model of this type to simulate other flows (eg, quasi-steady tidal flow, steady fluvial flow or purely oscillatory flow) is simple. For example, by setting the steady flow to 0m/s and running the model with purely oscillatory flow, the combined-flow forms lose any directionality (eg, bedform ends no longer point downstream) and become irregularly shaped lumps (Fig 2 top middle). This change in shape is also illustrated in the profiles of bedforms (Fig 3) taken along the solid lines in

Fig 2. The combined flow features show some directionality, with steep downstream faces and broader, more shallowly sloped upstream slopes (Fig 3a), but when the steady flow is removed they are no longer asymmetric (Fig 3b). Fluvial bedforms are simulated by setting the oscillatory amplitude to 0 m/s and using only steady flow. The predicted steady flow bedforms (Fig 2 top right) are highly asymmetric (Fig 3c) and similar in planform to observed bedforms (Fig 2, bottom right).

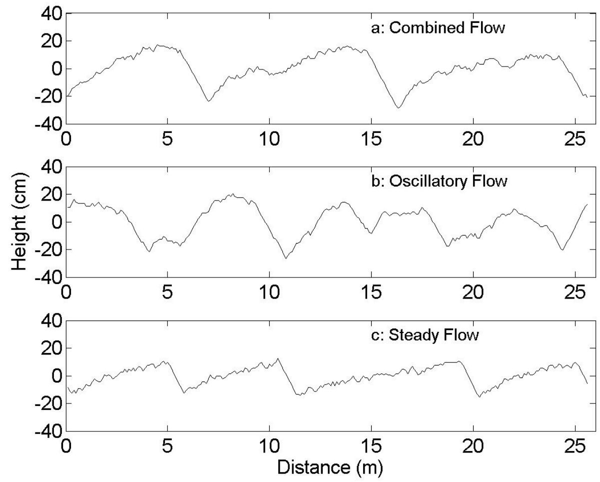

Figure 3. Profiles across simulated bedforms along lines marked in Fig 2(top panels). In c) steady flow profiles are highly asymmetric, while in a) that asymmetry is reduced by a superimposed oscillatory current. In b), with no steady flow at all, bedforms are symmetric in profile.

The model predicts that bedforms begin as random irregularities on the bed and, via feedback between the flow and the bed, coalesce into small bedforms. As bedforms continue to evolve, smaller, faster bedforms merge with larger, slower ones, causing crest- and wave-lengths to grow. Thus, younger bedforms tend to be short-crested, shorter in wavelength and irregular in shape, while more mature features are longer in both wavelength and crest length. This merging and lengthening is observed in nature (eg, Clarke and Werner 2004) and in other modeling studies (eg, Coco and Murray 2007, Werner and Kocurek 1999, Jerolmack and Mohrig 2005). Clarke and Werner (2004) observed that the growth of bedforms (wavelengths) from a flat bed to maturity occurred first linearly and then became logarithmic. This corresponds to the theoretical model of Werner and Kocurek (1999), which attributed the dynamics and growth of bedforms to the behavior of defects or the ends of bedform crests. The change in growth (from linear to logarithmic) was attributed to the growth and lengthening of bedform crests and the reduction in numbers of defects. The present model predicts this transition in growth rate (and the reduction in defect number), suggesting that the model captures well the bedform dynamics. The natural megaripples in Clarke and Werner (2004) made the transition at around 12 hrs. The modeled megaripples grow and transition much more quickly: 25 mins for sinusoidal flows and 50 mins for natural measured velocities (Fig 4).

The difference in growth rate of modeled megaripples driven with the sinusoidal versus the natural velocities may be explained by examining the velocity records. The largest amplitudes of the natural cross-shore velocity from the measured time series are over 100 cm/s and the root mean square (RMS) is 32 cm/s. The sinusoidal flows have amplitudes of 75 cm/s and a RMS of 65 cm/s. This difference is because the measured velocities are skewed (with the strongest flows having a short duration) and irregular, with the largest velocities (>75 cm/s) occurring infrequently. So, under natural flows, high transport rates are intermittent. In contrast, the sinusoidal flows reach their maximum velocity every cycle and drive high rates of sand transport consistently. Therefore, bedforms are built more quickly under the consistent sinusoidal flows and more slowly under the variable natural flows. Neither flow field reproduces the natural growth rate and transition time of 12 hrs observed by Clarke and Werner (2004). The long transition time observed in the natural surf zone likely results from the even higher variability of the total flow field, including more realistic turbulence, more realistic acceleration on the bedform crest (acting to reduce amplitude growth), variation in direction, variation in tidal level, which Clarke and Werner (2004) state is the dominant controller of the magnitude of the depth-dependent, wave-driven flows in the surf zone (Raubenheimer 2002), and possibly the frequent interruption of the feedback mechanisms by turbulence from breaking waves.

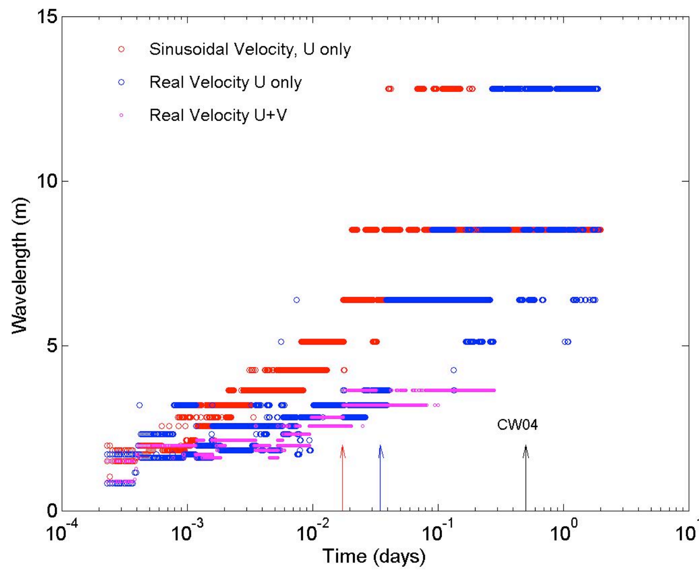

Figure 4. Bedforms wavelength growth with time. The black arrow marks the time for which Clarke and Werner (2004) found nearshore megaripples transitioned from early linear growth to later logarithmic growth (12 hrs). The red and blue arrows mark the transition times for sinusoidally (25 mins) and natural-flow (50 mins) driven bedforms, respectively. The magenta points are for bedforms driven by a directionally varying flow with the new 2D model. There is no quantitative transition time for these preliminary data, but it can be seen that they are growing more slowly than their 1D counterparts.

As part of the present study, adaptations have been made to the model to include more realistic flows and to allow the model to be scaled up (Fig 1). For example, by implementing 2-D flows and using the y-direction measured flows that correspond to the natural x-direction flows used in the calculations for Fig 4, the model was run and the model growth rate was slowed further (the magenta points fall below and to the right of the blue points in Fig 4). Note that this model run has not been completed for the long time needed to quantify this result so the transition time has not yet been determined. These preliminary results support the idea that variability of the bedform-building flows are important in understanding the growth and dynamics of the bedforms.

IMPACT/APPLICATION

This model is being adapted and applied to different environments. At this time the model is being expanded to be able to predict bedforms in larger scale more highly variable environments. For example, the flow field and conditions varyed significantly in time and in space during the New River Inlet experiment, including the deep sediment-starved channel with very strong, quasy steady, tidal flows and the waves-plus-tidal-flow-dominated shallow, sandy shoal that included breaking and directionally varying flows. Soon, the model will be compared with observations from these varied environments. This will be the first attempt at modeling tidal inlet and river mouth bedforms with the self organization model. It is expected that a simple model of this type could be expanded to model other environments. By beginning to work with CSDMS at this time, it is hoped that this model will be easily integrated into larger-scale flow and morphology models and will help improve the predictive capabilities of hydro- and morpho-dynamics in general.

RELATED PROJECTS

This work was originally supported by an NSF ADVANCE grant. At this time, ONR is the only granting agency for this work.

REFERENCES

Ahl, V. and T.F.H. Allen, 1996, Hierarchy Theory: New York, Columbia Univ. Press.

Bagnold, R.A., 1941, The physics of blown sand and desert dunes: Methuen and Co. Ltd. London

Bailard, J.A., 1981, An energetics total load sediment transport model for a plane sloping beach: Journal of Geophysical Research, 86, 10938-10954.

Best, J., 2005, The fluid dynamics of river dunes: A review and some future research directions. Journal of Geophysical Research, 110, F04S02, doi:10.1029/2004JF000218.

Clarke, L.B. and B.T. Werner, 2004, Tidally modulated occurrences of megaripples in a saturated surf zone: Journal of Geophysical Research, 109, C01012, doi:10.1029/2003JC001934.

Coco, G. and A.B. Murray, 2007, Patterns in the sand: From forcing templates to self organization: Geomorphology, 91, 271-290.

Coco, G., D.A. Huntley and T.J. O'Hare, 2000, Investigation of a self-organization model for beach cusp formation and development: Journal of Geophysical Research, 105, 21991-22002.

Ernstsen, V.B., R. Noormets, C. Winter, D. Hebbein, A. Bartholoma, B.W. Fleming, and J. Bartholdy, 2005, Development of subaqueous barchanoid-shaped dunes due to lateral grain size variability in a tidal inlet channel of the Danish Wadden Sea: Journal Geophysical Research, 110, F04S08, doi:10.1029/2004JF000180, 2005.

Frank. A. and G. Kocurek, 1996, Toward a model for airflow on the lee side of aeolian dunes. Sedimentology, 43, 451-458.

Gallagher, E.L., 2003, A note on megaripples in the surf zone: evidence for their relation to steady flow dunes: Marine Geology, 193, 171-176.

Gallagher, Edith L., 2011, Computer Simulations of Self-Organized Megaripples in the Nearshore, Journal of Geophysical Research-Earth Surface, 116, F01004, doi:10.1029/2009JF001473.

Gallagher, E.L., E.B. Thornton and T.P. Stanton, 2003, Sand bed roughness in the nearshore: Journal of Geophysical Research, 108, 3039, doi:10.1029/2001JC001081.

Gallagher, E.L., S. Elgar, and E.B. Thornton, 1998, Megaripple migration in a natural surf zone: Nature, 394, 165-168.

Hanes, D. M., 2012, The genesis of an inter-field marine sandwave and the associated anti-asymmetry migration of neighboring crests. Geopgysical Research Letters, 39, L04402, doi:10.1029/2011GL050641.

Hay, A.E. and D.J. Wilson, 1994, Rotary side-scan images of nearshore bedform evolution during a storm: Marine Geology, 119, 57-65.

Jerolmack, D.J. and D. Mohrig, 2005, A unified model for subaqueous bed form dynamics: Water Resources Research, 41, W12421, doi:10.1029/2005WR004329.

Kessler, M.A. and B.T. Werner, 2003, Self-organization of sorted patterned ground: Science, 299, 380-383.

Nemeth, A.A., S.J.M.H. Hulscher, R.M.J. Van Damme, 2007, Modelling offshore sandwave evolution. Continental Shelf Research, 27 (5), 713-728.
Ngusaru, A. S., and A. E. Hay, 2004, Cross-shore migration of lunate megaripples during Duck94: Journal Geophysical Research, 109, C02006, doi:10.1029/2002JC001532.
Nishimori, H. and N. Ouchi, 1993, Formation of ripple patterns and dunes by wind-blown sand: Physical Review Letters, 71, 197-200.
Parsons, D.R., J.L. Best, O. Orfeo, R.J. Hardy, R. Kostaschuk, and S.N. Lane, 2005, Morphology and flow fields of three-dimensional dunes, Rio Parana, Argentina: Results from simultaneous multibeam echo sounding and acoustic Doppler current profiling. Journal of Geophysical Research, 110, F04S03,doi:10.1029/2004JF000231.
Raubenheimer, B., 2002, Observations and predictions of fluid velocities in the surf and swash zones: Journal of Geophysical Research, 107, 3190, doi:10.1029/2001JC1264.
Reffet, E, S. Courrech du Pont, P. Hersen and S. Douady, 2010, Formation and stability of transverse and longitudinal sand dunes: Geology, 38, 491-494.
Ribberink, J.S., 1998, Bed-load transport for steady flows and unsteady oscillatory flows: Coastal Engineering, 34, 59-82.
Werner, B.T., 1995, Eolian dunes: computer simulations and attractor interpretation: Geology, 23, 1107-1110.
Werner, B.T., 1999, Complexity in natural landform patterns: Science, 284, 102-104.
Werner, B.T. and G. Kocurek, 1999, Bedform spacing from defect dynamics: Geology, 27, 727-730.

PUBLICATIONS

Abstracts and Presentations

Gallagher, E.L., Computer Simulations of Megaripples in the Nearshore. Abstract and Presentation at the International Conference on Coastal Engineering, Santander Spain, July 2012.

Gallagher, E.L., Computer Simulations of Bedforms. Presentation at the ONR Program Review, Denver CO, September 2012.

Peer-reviewed Publications

Gallagher, Edith L. (2011) Computer simulations of self-organized megaripples in the nearshore. *Journal of Geophysical Research Earth Surface*, 116, F01004, doi:10.1029/2009JF001473 [published, refereed].

Gallagher, Edith L., Jamie MacMahan, Ad Reniers, Jenna Brown, Edward B. Thornton. (2011) Grain size variability on a rip-channeled beach. *Marine Geology*, 287, 43-53 [published, refereed].

Elunai, Ronald, Vinod Chandran and Edith Gallagher. (2011) Asphalt concrete surfaces macro-texture determination from still images. *IEEE Transactions on Intelligent Transportation Systems*, 12 (3), 857-869 [published, refereed].

Reniers, A, E.L. Gallagher, J.H. MacMahan, J.A. Brown, A.A. van Rooijen, J.S.M. van Thiel de Vries and B.C. van Prooijen, Observations and modeling of steep-beach grain size variability: JGR Oceans, Sept 2012 [accepted, refereed].